Current Issues in Sport Science 1 (2016)

Origins and current issues in Quiet Eye research

Joan N. Vickers[1, *]

1 Faculty of Kinesiology, University of Calgary, Calgary, Canada
* Corresponding author: 2500 University Drive NW, Calgary, AB, Canada, T2N 1N4, Tel: +1 (403) 220-3420, Fax: +1 (403) 284-3553,
E-Mail: vickers@ucalgary.ca

MAIN ARTICLE

Article History:
Received 28th January 2016
Accepted 6th February 2016
Published 18th February 2016

Handling Editor:
Ernst-Joachim Hossner
University of Bern, Switzerland

Editor-in-Chief:
Martin Kopp
University of Innsbruck, Austria

ABSTRACT

All sports require precise control of physical actions and vision is essential in providing the information the movement systems needs to perform at a high level. Vision and focus of attention play a critically important role as the ability to direct the gaze to optimal areas in the playing environment, at the appropriate time, is central to success in all sports. One variable that has been consistently found to discriminate elite performers from their near-elite and novice counterparts is the Quiet Eye (QE). In the present paper, I first define the QE, followed by an explanation of its origins as well as the question: why have I pursued this one variable for over 35 years? I then provide a brief overview of QE research, and concentrate on QE training, which has emerged as an effective method for improving both attentional focus and motor performance. In the final section, I discuss some future directions, in particular those related to identifying the neural networks underlying the QE during successful trials.

Keywords:
sport – gaze – expertise – cognition – motor control – attention

Citation:
Vickers, J. N. (2016). Origins and current issues in Quiet Eye research. *Current Issues in Sport Science, 1:101*. doi: 10.15203/CISS_2016.101
This is the main article of a CISS target article. For retrieving the whole target article including index of contents, editorial, main article, all peer commentaries and author's response:
Hossner, E.-J. (Ed.) (2016). Quiet Eye research – Joan Vickers on target. *Current Issues in Sport Science, 1:100*. doi: 10.15203/CISS_2016.100

What is the Quiet Eye?

Sport is an arena where expertise has traditionally been defined by physical prowess. The bigger, stronger, and taller you are, then the better it is assumed you will be able to perform in most sports. But we have many examples of great athletes who were far from being the biggest, strongest or tallest, when compared to their teammates and opponents. Lionel Messi, Diego Maradonna, and Pele are three of the best soccer players in history, but are respectively, 5'7", 5'5", and 5'8" in height (Sibor, 2013). Wayne Gretzky is considered one of the world's greatest hockey players, but he tested at the bottom of his team in speed, aerobics, strength and other physical measures of prowess. Ken Dryden, a competitor of Gretzky explains that "he knew he wasn't big enough, strong enough, or even fast enough to do what he wanted to do if others focused on him. Like a magician, he had to direct attention elsewhere, to his four teammates on the ice with him, to create the momentary distraction in order to move unnoticed into the open ice where size and strength didn't matter. Gretzky made his opponents compete with five players, not one, and he made his teammates full partners to the game" (Dryden, 1998, p. 98). Gretzky himself put it best: "I couldn't beat people with my strength; I don't have a hard shot; I'm not the quickest skater in the league. My eyes and my mind have to do most of the work" (Gretzky & Reilly, 1990, p. 128). This quote illustrates how cognitive capacities, and specifically the control of the gaze and attention, play an important role in distinguishing good performers from the greatest. In all sporting activities, elite performer are able to focus intently not only on *what* location is most relevant, but also *when* information from that location must be accessed and for how long, relative to the phases of the movement.

The QE has five characteristics that are measured, *in situ*, using a light mobile eye tracker that is coupled to an external motor camera (Vickers, 1996a, 1996c, 2007). For a given motor task, the QE is defined as the final fixation or tracking gaze that is located on a specific location or object in the task space within 3° of visual angle (or less) for a minimum of 100 ms. The onset of

2016 | *innsbruck* university press, Innsbruck
Current Issues in Sport Science | ISSN 2414-6641 | http://www.ciss-journal.org/
Vol. 1| DOI 10.15203/CISS_2016.101

the QE occurs prior to a critical final movement in the task and the offset occurs when the gaze deviates off the object or location by more than 3° of visual angle for a minimum of 100 ms, therefore the QE can carry through and beyond the final movement of the task. The QE of elite performers is significantly longer than that of near-elite or lower skilled performers, meaning those who consistently achieve high levels of performance have learned to fixate or track critical objects or locations for earlier and longer durations irrespective of the conditions encountered. The onset of elite performers is invariably earlier, indicating they have found a way to see critical information sooner, thus enabling the transmission of a higher quality commands to the motor system. The QE of elite performers has an optimal duration given the constraints of the task, meaning it varies in length depending on the specific motor task (for an overview, see Vickers, 2007).

In a typical QE study, the first step is to test elite athletes in a well-known task, thereby establishing norms from which training and other interventions can be based. Critically, the athletes perform, *in situ*, until an equal number of successful and non-successful trials are recorded. Therefore, one must first define success and failure in the *task* as defined by experts, using independent statistics established in the sport. These are very easy to access today in almost any sport. Once sport specific statistics are known, it is relatively easy to define successful and unsuccessful performance in the sport. For example, as I write this paper, the top athlete in golf putting is Jordan Spieth, who averaged 1.7 putts per hole during the 2015 season (PGA Tour, 2016). In archery, Kim Woojin is the current Olympic champ, averaging 9.5 out of 10 (World Archery, 2016). In the basketball free throw, the all-time NBA leader is Steve Nash, who sunk 90.4% of his free throws during a 10 year career (LLC, 2016). In the 2014-2015 NHL season, Carey Price was the best goaltender stopping 93.0% of shots (ESPN, 2016). Because statistics like these exist in sport more than in other domains, the unique QE characteristics of elite performers could be discovered, and distinguished from their lesser skilled, but often more physically gifted "near-elite" teammates. For example, in archery, hits could be defined as those in the 10 and 9 rings (as this level of accuracy can lead to an Olympic medal), whereas anything below 9 would be treated as a miss.

Origins of the QE

I began my quest toward the QE during my PhD program at the University of British Columbia, where I was able to take courses from some of the world's greatest cognitive scientists, including Anne Treisman (Treisman & Gelade, 1980), and Dan Kahneman (Kahneman, 1973, 2011). Stan Coren (Coren, Ward, & Enns, 2003), a perception psychologist and eye tracking specialist was my research supervisor and taught me how to record the eye movements of elite gymnasts and soccer players who sat, head still in a chin rest and scanned a sequence of slides from gymnastics (Vickers, 1988). Only a few people understood why I carried out the study, and there were days when I wondered myself, but I realize now I used eye tracking as a way to access to the brain and what today we call the mirror neuron system (Rizzolatti, Fadiga, Gallese, & Fogassi, 1996).

Although my experiences at UBC were exceptional, and laid the foundation for the QE, they do not explain why I have pursued this one variable for so long. Prior to beginning my PhD, I spent five years as a teacher and coach in the public schools, followed by five years as an athletic director and teacher educator at the university level. In those roles I became familiar with the many challenges athletes, coaches and students face. In particular, I became aware of a deficiency in motor learning and control research, which at that time, had not moved out the laboratory and provided little or no assistance to the young teachers and coaches I was teaching who were about to enter the work force. When I started my PhD, I was determined to find a way to conduct experiments in real world sport situations.

My early, applied experiences motivated me to look outside the existing research paradigms, but what has stayed with me all these years is that I know deep down that humans possess the ability to perform at levels way above what they are usually capable of. I know this because I had three experiences myself, as an athlete, in which I performed well above what I had normally achieved. As an undergraduate, I was fortunate to play four years of varsity volleyball and four years of varsity basketball. My first experience occurred during a volleyball game when I served the whole game from the first server position. As the pressure built toward the end of the game, I remember the only thing that was important was to keep my eye on the lower back of the ball where the heel of my hand made contact during the float serves I was delivering. The second occurred in a basketball game when I scored 27 points in a single game (which was 100% above my best result ever), and the last was in alpine skiing when I had a perfect run in deep moguls on a big mountain. As each of the events unfolded I was absolutely sure I had mastered the sport, but it was all gone the next day! Actually it was all gone on the next run. I have asked audiences if they also have had one of these "out of body", "one with the target", "in the zone", "zen" or "flow" experiences and many raise their hands. Research exists on the phenomena, with one approach being the "hot hand in sport" (Gilovich, Vallone, & Tversky, 1985), but overall there is little evidence in support. However, these studies looked at game statistics, whereas the QE is a perception-action, neural-cognitive variable. In this paper I am going to suggest that the QE is the reason the "hot hand" exists, and why having one is a fleeting experience for a mere mortal like me, as well as for most people reading this paper. But if you are an elite athlete, defined as someone who has the very best statistics in the world in a specific sports task, then you possess a "hot hand" (and QE) most of the time.

QE becoming a significant research topic

Insight into the QE first emerged in golf putting (Vickers, 1992), although I did not use the "Quiet Eye" term in that study. The term first appeared in papers on the basketball free throw (Vickers, 1996a, 1996b, 1996c), followed by the volleyball serve reception (Adolphe, Vickers, & LaPlante, 1997; Vickers & Adolphe, 1997) as I wanted to see whether the concept applied to targeting and interceptive timing skills. Today, twenty years after the first QE study was published, a meta-analyses has described the QE as one of three gaze behaviors that consistently differentiates experts from their non-expert counterparts (Mann, Williams, Ward, & Janelle, 2007). On average, experts maintained a QE duration that was approximately 62% longer than nonexperts. Recently, Rienhoff, Tirp, Strauss, Baker, and Schorer (2015) have carried out a systematic review of the QE, linking it to Newell's model of interacting constraints (Newell, 1986). Three electronic databases were searched from inception until February 2015. A total of 580 QE records were found, indicating the tremendous growth in the area over the past few years. In addition, a number of comprehensive reviews of the QE have been completed (see Causer, Janelle, Vickers, & Willams, 2012; Wilson, Causer, & Vickers, 2015).

QE in targeting tasks

In targeting tasks, the function of the gaze and attention system is to locate a target in space and to control the aiming of an object to the target area. In these tasks an object is usually propelled with the hands or feet away from the body in an aiming movement toward a target. Accuracy and consistency in performance are the ultimate goal in tasks such as shooting a basketball, performing a golf putt, throwing a dart, shooting a rifle or bow, or throwing to a receiver. Although the motor behaviors differ markedly in each case, the problem for the gaze and attention system is the same: to focus on the most critical part of the target and acquire specific information so that there is an optimal coupling between the gaze and aiming movements, thus leading to successful completion of the task. The ability to accurately select the correct cues for movement is crucial for successful performance. The additional time needed for a longer QE duration is most often accomplished by having an earlier QE onset, before the critical movement and not necessarily extending the absolute processing period, within the time available.

A recent study in golf putting used an instructional approach to investigate the advantage of an "effect-related" versus "movement-related" focus on golf performance (Klostermann, Kredel, & Hossner, 2014). Expert and near-expert golfers were provided with both movement-related instructions in which their attention was drawn internally to the movement of the arms, and effect-related instructions, which directed their attention to swing and contact with the ball. No overt instructions were given regarding the QE. Putting performance was to a target at 3 m and accuracy was measured using radial error. Performance was significantly better for both groups during the effect-related condition. QE duration was longer for the experts than near-experts. QE offset occurred later for the experts. A new variable called QE efficiency was determined using correlation coefficients between the QE parameters and putting performance. An *inhibition hypothesis* was proposed, which states that the long QE duration could be explained as "the need to inhibit alternative movement variants so that only the optimal variant gets parameterized" (p. 398). Since the golf putt requires exquisite control, often under extreme pressure, the inhibition hypothesis makes sense. Whether this applies to other skills will be interesting to see (for a summary of the optimal QE location, onset, offset and duration in a number of other targeting tasks, see Wilson et al., 2015).

Interceptive timing tasks

In interceptive timing tasks, an object travels toward the performer and the gaze and attention systems are used to read the object as it is delivered, track it as it approaches, and then control it as it is received, for example as it occurs in goaltending in soccer or ice hockey; hitting a baseball or cricket ball; receiving serves in volleyball, tennis or badminton; or receiving a pass in soccer, basketball and many other sports. Interceptive timing tasks have three sequential phases in common: object recognition, object tracking, and object control (Vickers, 2007). During the object-recognition phase, fixations and pursuit tracking are used to study the movements of the object and of the individual propelling the object, as it is pitched, bowled, kicked, shot, or otherwise propelled toward the receiver. During the object-tracking phase, smooth pursuit-tracking eye movements are used to maintain the image of the object on the fovea in order to detect if it spins; accelerates or decreases in speed; changes direction; or is affected by wind, sun, or a host of other factors that can occur. Pursuit tracking differs according to whether object flight is predictable or unpredictable. When the flight of the object is predictable, early tracking is usually sufficient to ensure control of the object at reception. However, when it is unpredictable, early tracking, plus saccadic movements and late tracking eye movements on the object are critical (Land, 2009). During the object-control phase, the object is caught with the hand, kicked to a teammate, hit as in baseball or cricket, passed to a teammate as in volleyball, and so on. Many interceptive timing tasks in sport require the object to be directed to a secondary target at contact.

Predictions of object flight are often made before the object starts moving, such as by the goal keeper in penalty kicks, based on early postural cues of the opponent (Causer & Williams, 2013), which can then be corroborated by early ball flight information. However, in most interceptive tasks, early detection of the target followed by a continuous tracking of the object seems to be the most effective strategy. For example, in a series of studies, Causer et al. (Causer, Bennett, Holmes, Janelle, &

Williams, 2010; Causer, Holmes, Smith, & Williams, 2011; Causer, Holmes, & Williams, 2011) examined the gaze strategies of expert and less-expert shotgun shooters. Analysis of eye movement data showed that expert shooters demonstrated an earlier object pick up, and a longer object tracking (QE duration) when compared to their less-expert counterparts. Successful shots were characterized by similar properties for high and low skill levels compared to unsuccessful shots, demonstrating that this gaze strategy is the most effective.

Researchers have shown similar findings in other interceptive tasks, such as in ice hockey goaltending (Panchuk & Vickers, 2006), table tennis returns (Rodrigues, Vickers, & Williams, 2002) and volleyball serve receptions (Vickers & Adolphe, 1997). Panchuk and Vickers (2006) found QE duration was longer on saves for eight of eight goaltenders, compared to goals. An early onset of QE and longer QE duration is critical for the successful interception of rapidly moving objects: the early QE onset maximizes the tracking time, and enables early flight information to be processed, while a longer QE duration provides sufficient time for flight trajectory information to be accurately calculated (for a summary of the optimal QE location, onset, offset and duration as exhibited by elite or expert performers in interceptive timing tasks, see Wilson et al., 2015).

QE training

Since expert performers have QE characteristics distinct from those with lower skill levels, QE training is designed to help non-experts acquire the most optimal spatial information, thus allowing the neural structures underlying the action to optimally organize. When the spatial information is insufficient or incomplete, then the action is only partially organized and performance suffers. Paradoxically, the type of gaze control that accompanies excellence in motor skills is not itself rapid and dynamic, but instead just the opposite. Even for skills that are rapid and ballistic, like making a save in ice hockey goaltending (Panchuk & Vickers, 2006), the final fixation onset is early, on a specific location (the puck on the stick before it is released) and has a duration longer as the elite performers focuses intently on a specific task location in space well before the final phase of the movement begins.

Since the human brain is a relatively slow visual processor, it is incumbent on the performer to find ways to access complex spatial information earlier and under conditions that can be very difficult to access. QE training studies are designed to help novice to near-expert athletes adopt the QE focus of elite performers earlier, thus accelerating skill acquisition and performance. Origin of the QE norms are derived from research with elite performers. A QE training program is carried out in seven steps:

1. *Define expert QE prototype*. The first step is to isolate the five QE characteristics of elite and near-elite performers in the task during successful and unsuccessful trials. Near-elite athletes are those with similar physical attributes as the elite (usually a teammate), but with lower statistics in the task during a season of play.
2. *Test trainees in the same task*. The trainee is tested in the same task using a mobile eye tracker and a motion analysis system in conditions similar to those used in step 1.
3. *Provide instruction of the five QE characteristics*. The trainee should be shown the QE video data of an elite QE prototype (derived from step 1). A QE prototype illustrates the results for the elite group for QE location, onset, final critical movement, offset and duration. Carefully teach the trainee the importance of the five QE characteristics, using the frame-by-frame video controls.
4. *Provide QE feedback*. Video feedback is used to show the trainee his/her own QE as collected in step 2. Compare the trainee's QE to the elite prototype using side-by-side QE videos. An important part of this step is to ask trainees questions about their QE location, onset before a specific phase, offset, and duration. How does their QE differ from the elite prototype using frame-by-frame video comparison? The key is to cognitively probe how much the athletes understand about the control of their attentional focus as they perform.
5. *Decision training*. The trainee decides which of the five QE characteristics he/she wants to work on first. This is an important step as it passes control to the athletes in terms of learning how to master their attention. Re-test often using the eye tracker and plot improvements.
6. *Blocked and random training*. Blocked training drills are designed to promote the desired QE focus in repetitive trials with little variation. As the five QE characteristics must be mastered in a variety of game situations, design variable and random drill that are game like. Use bandwidth feedback and questioning as QE control improves (Vickers, 2007).
7. *Assess competitive QE*. Performance in competition should be assessed and follow-up QE tests carried out, as needed, designed to improve the athlete's performance in a variety of real-world competitive situations.

The first study to use QE training was in the volleyball service reception and pass (Adolphe et al., 1997; Vickers & Adolphe, 1997). Initial testing showed that players with higher service reception statistics tracked the ball earlier and for a longer duration. To facilitate early detection of the ball and improve tracking, a number of drills were developed where players were asked to track small objects, identify numbers placed on balls as they were served, and identify numbers when less time was available (i.e., the server was occluded by a blackboard or the receiver had to turn 180° after the serve). One month after completion of the training exercises, players were tested again on court and the results showed that all of the athletes were able to track the ball earlier and longer. Pass accuracy during competition also improved 7% over a three-year span following the study whereas a comparison group of top international athletes who did not receive the training remained relatively stable over that period of time.

The second study in which we used QE training was with elite and near-elite varsity basketball players (Harle & Vickers, 2001). We found a significant increase in QE duration and free-throw accuracy in the experimental setting in year one, followed in the second year, by an increase in free throw-accuracy in games from 54% to 76% (an increase of 22%, which was significantly higher than two control teams who did not receive a similar training). The amount of improvement in this study was considerable and shows that athletes who are trained to control their gaze, attention and decision making while performing in drills that simulate events within the game achieve gains that are much greater than when physical and/or psychological training are used alone.

Table 1 presents an overview of QE training information used in eight sport and motor activities, and the specific QE characteristics (location, onset, offset, critical movement, and duration) as derived from elite or expert performers in each task.

Table 1: Recommended QE Location, onset before critical movement, offset and duration during QE training in selected motor tasks. The QE norms were derived from research with elite performers in each motor task.

Author(s)	Sport or motor Activity	Who was trained?	QE location	QE onset before which critical movement?	QE offset	QE duration (retention or transfer tests)
Adolphe, Vickers & LaPlante (1997)	volleyball serve reception	national volleyball team	ball as it is being served and during early flight	ball at location of contact by server's hand and during early flight	early if ball flight is predictable; late, before contact, if ball flight is unpredictable	400-500 ms, depending on speed of ball
Harle & Vickers (2001)	basketball free throw	varsity basketball team	front of rim	before shot is initiated	before final extension of elbow and the shooting hand	1.0 s
Vickers, (2007); Vine & Wilson (2011)	golf putting	high and low skilled golfers	back or top of ball	before backswing	after club/ball contact for 300 ms	2.5 s on short putt; 3.0 s on long putt
Causer, Holmes, & Williams (2011)	skeet shooting	elite olympic shooters	1st clay as soon as it is launched; detect 2nd clay immediately after trigger pull	250 ms before trigger pull	after trigger pull	400-425 ms on each clay
Wood & Wilson (2011)	soccer penalty kick	university level athletes	(A) top left or right corner of net; (B) on ball where foot will make contact	(A) before beginning of run-up; (B) during run-up before backswing of kicking leg	(A) not reported; (B) not reported	(A) 900 ms (B) 700 ms
Causer, Harvey, et al. (2014); Causer, Vickers, et al. (2014)	surgical knot tying	surgical residents in first month of 5 year program	location in tissue where the first knot is to be placed	before placing the first knot	after all throws (usually 3 or more are completed)	2.5 s
Miles, Vine, Wood, Vickers, & Wilson (2014, 2015a)	throw a ball at a blank wall and catch it before the bounce	typical children; aged 9-10	targeting: "virtual target" on the blank wall; ball flight: ball as it left the wall	targeting: before the underhand throw; ball flight: before the ball left the wall	targeting: after ball hits the wall; ball flight: before the catch	targeting: 700 ms; ball flight: 300 ms
Miles, Wood, Vine, Vickers, & Wilson (2015b)	throw a ball at a blank wall and catch it before the bounce	children with development coordination difficulties; aged 9-10	targeting: "virtual target" on the blank wall; ball flight: ball as it left the wall	targeting: before the underhand throw; ball flight: before the ball left the wall	targeting: after ball hits the wall; ball flight: before the catch	targeting: 500 ms; ball flight: 200 ms

QE in child development

The most recent QE training studies have been in child development, and included typically developing children, as well as those with developmental coordination disorder (DCD) (Miles, Vine, Wood, Vickers, & Wilson, 2014; Miles, Wood, Vine, Vickers, & Wilson, 2015a, 2015b; Wilson, Miles, Vine, & Vickers, 2013). These studies are important as they show that QE training can be used with young children, thus opening up new methods for coaching the developing athlete. These studies also provide a preliminary answer to a question I am often asked when I speak at conferences: Is the QE genetic or acquired? I always respond that I do not know but research needs to be done in the area. In particular, we do not know if some children are born with the ability to focus in an exceptional way from any early age, or if this is an acquired ability that occurs with extensive training and practice. I have taught children with DCD and they find it difficult to perform motor skills and have witnessed the stigma and helplessness they often feel. Therefore another motivation was to see whether we could develop QE training programs that might be beneficial to this group of children. My very first gaze study was in child development, where we found differences in the gaze of children in the top percentile of a motor battery of skills compared to those at the very bottom (Emes, Vickers, & Livingston, 1994). Finally, although extensive DCD research has been carried out, the assumption is that the observed deficit exists primarily at the motor level, rather those related to the gaze and focus of attention.

If you have ever wondered what it is like to have DCD, try this exercise. Stand about 2 m from a blank wall. Look down at a tennis ball you are holding in your throwing hand. Throw it underhand at the wall but do not look up until the ball is about to hit the wall. Try to catch the ball before it hits the floor. Pretty hard, right? We found this is what some children with DCD experience, as opposed to what typically occurs in developing children. On your second attempt, hold the ball in your throwing hand, and look at the wall and in your "mind's eye" create a "virtual target" on the wall. Throw the ball so it hits the target you have created. Catch the ball before it hits the floor. Much easier, right? This is the task we used in three studies in which the participants were typical children and one study in which the children were diagnosed with DCD (Wilson et al., 2013). The throw and catch task we used is a part of the battery of motor skills (Henderson, Sugden, & Barnett, 2007) which combines both a targeting and an interceptive timing component. The participants in all four studies were aged 9-10, equal boys and girls.

In the first study, we found that children who performed in the highest percentile group (in % of successful catches) had a QE duration on their "virtual target" on the wall of about 700 ms *which occurred before they threw the ball*, while those in lowest percentile had a QE duration of about 250 ms, barely the threshold of visual reaction time. In the second study, typical children were randomly assigned to a QE training (QET) group or a technical training (TT) group. The TT participants were provided with technical information about how to control their arm movements during the throw and catch phases, while the QET participants were in addition taught to fixate a target location on the wall prior to the throw, followed by early tracking the ball prior to the catch. After training, QE duration increased and the percentage of catches increased to 72% for the QET group, whereas the TT group's QE remained the same as the pretest for both groups at around 50%, or chance. In the third study, children with DCD underwent similar QET or TT programs. The QET group increased QE duration and improved catching mechanics, whereas the TT group experienced a reduction in QE duration and no improvement in technique. The fourth study involved typical children and assessed the retention of skills acquired using QET and TT after a two month period. The QET participants had a significantly longer QE duration on the wall, an earlier QE as they tracked the ball, and a high percentage of catches, while the TT group revealed no improvements in QE or catching. Further analyses showed it was the first QE on the wall that was most important, pointing to the importance of anticipation and an early QE focus of attention on a specific target prior to the initiation of the throwing action. Response to these papers has been very positive. It is recommended that QE training programs are developed and applied to other motor tasks important in child development and sport. However, our results do not provide an answer to the question whether QE is genetic or acquired. This is a worthy research question and hopefully one that scientists with a background in child development and genetics will undertake.

QE and performing under high pressure and anxiety

An important characteristic of expert performers is their ability to perform under intense competitive pressure. The QE has also been identified as a gaze affected by high levels of performance pressure and anxiety (Behan & Wilson, 2008; Vickers & Williams, 2007). Vickers and Williams (2007) assessed the QE of elite biathlon shooters separately during high-pressure (national team tryouts) and low-pressure (practice) conditions in which physiological workload increased to 100% of their individual maximum. Anxiety levels were elevated for all the athletes under high pressure, and all but three choked at the 100% workload (shooting 29%). Those that did not choke shot 80% and increased their QE duration on the target by 600 ms. Behan and Wilson (2008) found a similar QE result in a simulated archery task under conditions of elevated cognitive anxiety. Other QE studies have confirmed and extended these results (Moore, Vine, Cooke, Ring, & Wilson, 2012; Moore, Vine, Wilson, & Freeman, 2012; Moore, Wilson, Vine, Coussens, & Freeman, 2013; Vine, Lee, Moore, & Wilson, 2013).

Theoretically, it is thought that high anxiety causes a diversion of processing resources from task-relevant stimuli toward task-irrelevant and/or threatening stimuli, which may be external in the environment or internal through worrying thoughts (Eysenck, Derakshan, Santos, & Calvo, 2007; Wilson et al., 2015). According to their *attentional control theory* (ACT), anxiety alters the strength of output so that threat-related stimuli are more likely to capture attention thereby increasing the sensitivity of the stimulus-driven ventral system, at the expense of goal-directed control by the dorsal attention system (Corbetta, Patel, & Shulman, 2008; Corbetta & Shulman, 2002). In terms of QE, this increased sensitivity of ventral attention is likely to disrupt efficient QE processing, and subsequent visuo-motor performance (see Wilson et al., 2015, for a summary of QE anxiety studies completed to date).

What are the neural structures underlying the QE?

With the advent of advanced imaging methods, the neural networks underlying visuo-motor control are increasingly better known, providing a theoretical basis for defining the networks that may be functioning during the QE period (Kolb & Whishaw, 2009, 2013; Liversedge, 2011). Task-specific spatial information is registered first on the retina, then passed through the optic nerve, the lateral geniculate nucleus, and the optic radiations to the visual occipital cortex at the back of the head. Located in the occipital cortex are feature detectors V1-V8 that register what the performer is looking at. V1 is responsible for the initial registration of features, which are then processed by V2 for shape, V3 for angles, V3a for motion, V4 for color, V5 for motion with direction, V6 for depth and self-motion, V7 for stereo motion, and V8 for further color-responsiveness. V1 to V8 processing is highly individualized, influenced by the type of training received, by current conditions and by a host of other factors.

Once an object, person or location is registered, visual information travels rapidly forward along two visual networks, the dorsal attention network (DAN) and the ventral attention network (VAN) which run in parallel (Astafiev, Stanley, Shulman, & Corbetta, 2004; Corbetta et al., 2008; Corbetta & Shulman, 2002). The DAN is faster than the VAN and projects from the occipital lobe to the parietal lobe and forward to the frontal lobe in a journey in which the frontal eye fields and areas in the frontal lobe sustain focus on critical cues in space. During the QE the primary function of the DAN is thought to focus attention on specific locations in space, as well as to sustain intentions generated internally. With practice and the development of expertise, it is thought that the DAN system blocks or suppresses distracting or anxiety-producing stimuli that may intrude from the VAN system. The VAN projects forward through the temporal lobes to the frontal areas, and includes the hippocampus and amygdala. Both the hippocampus and amygdala are responsible for encoding memories (both good and bad). The hippocampus converts short-term memories to long-term and distributes them throughout the brain in areas involved in their origin, while the amygdala is the seat of emotional control. An athlete who has had a particularly bad experience may have negative memories registered by the hippocampus and amygdala. Following DAN/VAN processing motor commands are developed in the frontal cortex and passed on to the motor cortex, which initiates the action (Callaert et al., 2011; Woolley et al., 2010). During the complete visuo-motor process outlined above (from retina to motor cortex) the lower centers in the basal ganglia and cerebellum are also on-line and take over automatic and other forms of control. As is evident from the description above, visuo-motor control dominates the brain, both in terms of its structures but also its processes.

Four lines of evidence

Research evidence that confirms the brain undergoes extensive change as a result of training in sport is in it’s infancy. Studies that do exist fall into four categories. EEG/ERP (electroencephalography/event related potentials) studies determine cortical processing differences as elite and novice athletes prepare to execute a skill, such as the golf putt or shooting in archery. MRI (magnetic resonance imaging) studies on high and low skilled athletes require the athlete to passively lie in the scanner in an effort to identify structural differences caused by extensive training in a specific sport. fMRI (functional magnetic imaging) studies attempt to identify the neural structures of elite and novice athletes as they watch an event from their sport, for example a video of a motor task that is temporally or spatially occluded. Participants are required to make a decision, for example, to identify the direction of a serve by pressing a button. Other fMRI studies require athletes performing a simulated sports task, for example, using a joystick to shoot at a target in archery. As will be shown in the following, very few studies have imaged the brain during the QE period.

The first, and perhaps only study to assess the QE and EEG used event-related potentials (ERP) to pinpoint the locus of attention and temporal activation during the preparation of putts performed by low (LH) and high (HH) handicap golfers (Mann, Coombes, Mousseau, & Janelle (2011). They measured a specific type of ERP called the Bereitschaftspotential, which is a moment of heightened processing which precedes an actual, intended, or imagined event by 1 s to 1.5 s thereby indexing anticipatory attention and movement preparation. Electrodes were placed over C3 and C4 in the left and right motor cortex, as well as the P3 and P4 in the left and right parietal areas. The LH group not only performed better on the putting task, but also had a longer QE duration relative to the HH group, accompanied by greater cortical activation in C3 (right motor cortex) and C4 (right parietal lobe). Mann et al. (2011) state that during the QE period, highly skilled golfers “allocated more attention to the visuo-motor components of the putting task than their HH counterparts … [which] reflects attentional processes that permit the assessment, organization, and recall of the requisite motor program from memory” (p. 231).

Second, Jäncke, Koeneke, Hoppe, Rominger and Hänggi (2009) scanned four groups of golfers using MRI: 10 professional golfers (handicap 0), 10 highly-skilled golfers (handicap range 1–14), 10 golfers at the intermediate level (handicaps 15–36), and 10 individuals with no golf experience. Significant differences were found between the two higher skilled groups when compared to the two lower skilled. The authors found that neuro-anatomical changes had been induced by intensive practice in golf. The high skilled groups had larger volumes of grey and white matter in the right and left fronto-parietal networks, including premotor and parietal areas. In addition, they had lower volumes of fibers running from the thalamus to the frontal lobe, which regulates emotion, attention, and basic movement processes, suggesting less reliance on working memory and more on automated control processes. In a second MRI study, novice golfers were trained for 40 hours of golf practice and play and compared with a control group who received no practice in golf (Bezzola, Merillat, Gaser, & Jäncke, 2011). The pre/post MRI comparison showed significant increases associated with the DAN network, specifically in areas of the supplementary area and motor cortex, as well as the pre-motor cortex and left and right inferior parietal lobes. There was no measure of the QE in these studies.

Third, in a series of three studies, fMRI was used to identify the neural areas activated in viewing and responding to video sequences of participants filmed from the view of the athlete receiving serves in tennis and in badminton (Wright, Bishop, Jackson, & Abernethy, 2010, 2011; Wright & Jackson, 2007). Elite and novice participants determined the direction of the serves as quickly as possible by pressing a directional button. Experts showed greater activation in brain areas associated with visual attention and the analysis of body kinematics, specifically superior parietal cortex, the middle and superior temporal sulcus, which control smooth pursuit processing, as well as object recognition, motion detection, and depth perception. Conversely, the novices had higher activation in the occipital cortex, suggesting a greater influence of bottom-up processing based on the perception of distinct features rather than an overall top-down understanding of what was being viewed. There was no measure of the QE in these studies.

Finally, the overall goal of a study by Gonzales et al. (2015a, 2015b) is to carry out an fMRI study in which a valid archery simulator activates the brain structures and processes used during the QE period. Two of three experiments have been completed so far. In study 1, expert and novice archers took shots to a regulation target set at 30 m, and in study 2 shots were taken using a computer simulator and joystick. Results were similar in the two tasks. Experts were more accurate than the novices, as expected, and had a longer mean QE duration and earlier onset. The authors conclude that the longer QE durations may facilitate the integration of information for the formulation of a motor program, as part of a feed-forward/feed-back system. In the fMRI study, Gonzalez et al. (2015b) have hypothesized that enhanced activation of the dorso-fronto-parietal network will occur in expert archers more than in non-experts, that is associated with top-down processing and the allocation of attention to relevant stimuli and the suppression of distractors in the ventral stream due to bottom-up processing. They do not specify whether this will occur for the experts and novices over all trials (using radial error, i.e., hits and misses combined), or whether the QE will differ for experts and novices on accurate trials, as opposed to misses. If I were to predict the outcome, I would expect significant differences for the experts on hits versus misses, as hypothesized above, but not for novices, as they have not developed the neural networks that will allow them to be accurate over a number of trials, which will be relatively easy for the experts in the simulator condition. If QE is determined when accuracy is calculated using hits and misses combined (i.e radial error), the results will not be as clear as when an absolute measure of accuracy is used (i.e 10 hits versus 10 misses), as normally occurs in QE studies. Results are forthcoming in 2016.

Conclusion

At the outset I talked about three experiences I had in sport when I performed at a level way above anything I had achieved in the past, experiencing for fleeting moments what is commonly called the "hot hand" in sport. As a result of those experiences, I knew that some secret power resides within all of us on occasion, but is probably present in elite athletes and other experts most of the time for reasons we did not understand. Now 35 years later, the QE may provide an objective measure of the "hot hand" in sport. With the attainment of sports expertise, measureable changes occur in the visuo-motor networks and QE as a consequence of extensive training and real world competition. Because the QE onset occurs prior to the final critical movement, and is of longer duration when performance is higher, the QE period represents the window of time when the neural networks are organized prior to and during motor execution. In this view the neural networks underlying high levels of performance are "fed" very precisely with external visual information, and it is this information that is central to organizing the complex neural systems underlying control of the limbs, body and emotions. An analogy I often use describes the QE as a "GPS system" that feeds the brain with the optimal spatial information needed for the action to be effectively organized, initiated and controlled. When the location, onset before a critical movement, offset and duration of the QE are all optimal then the resultant performance is superior; when any one of these QE dimensions is non-optimal then performance will suffer.

My last point is that, to date, the QE has been isolated in approximately 28 motor tasks, which means there are many QE discoveries yet to be made when one considers the many sports that humans participate in. Although understanding the neural and other processes underlying the QE is important, it is also vitally important that we continue to isolate the QE of elite performers in sport, medical, law enforcement and other motor tasks, followed by developing QE training programs that are effective with different age and skill levels, as well as for disability groups and rehabilitation programs.

Funding

The author has no funding or support to report.

Competing Interests

The author has declared that no competing interests exist.

Data Availability Statement

All relevant data are within the paper.

References

Adolphe, R. A., Vickers, J. N., & LaPlante, G. (1997). The effects of training visual attention on gaze behaviour and accurcy: A pilot study. *International Journal of Sports Vision*, *4*, 28-33.

Astafiev, S. V., Stanley, C. M., Shulman, G. L., & Corbetta, M. (2004). Extrastriate body area in human occipital cortex responds to the performance of motor actions. *Nature Neuroscience*, *7*, 542-548. 10.1038/nn1241

Behan, M., & Wilson, M. (2008). State anxiety and visual attention: The role of the quiet eye period in aiming to a far target. *Journal of Sports Sciences*, *26*, 207-215. 10.1080/02640410701446919

Bezzola, L., Merillat, S., Gaser, C., & Jäncke, L. (2011). Training-induced neural plasticity in golf novices. *The Journal of Neuroscience*, *31*, 12444-12448. 10.1523/JNEUROSCI.1996-11.2011

Callaert, D. V., Vercauteren, K., Peeters, R., Tam, F., Graham, S., Swinnen, S. P., & Wenderoth, N. (2011). Hemispheric asymmetries of motor versus nonmotor processes during (visuo)motor control. *Human Brain Mapping*, *32*, 1311-1329. 10.1002/hbm.21110

Causer, J., Bennett, S. J., Holmes, P. S., Janelle, C. M., & Williams, A. M. (2010). Quiet eye duration and gun motion in elite shotgun shooting. *Medicine & Science in Sports & Exercise*, *42*, 1599-1608. 10.1249/MSS.0b013e3181d1b059

Causer, J., Harvey, A., Snelgrove, R., Arsenault, G., & Vickers, J. N. (2014). Quiet eye training improves surgical knot tying more than traditional technical training: A randomized controlled study. *The American Journal of Surgery*, *208*(2), 171-177. 10.1016/j.amjsurg.2013.12.042

Causer, J., Holmes, P. S., Smith, N., & Williams, A. M. (2011). Anxiety, movement kinematics, and visual attention in elite-level performers. *Emotion*, *11*, 595-602. 10.1037/a0023225

Causer, J., Holmes, P. S., & Williams, A. M. (2011). Quiet eye training in a visuomotor control task. *Medicine & Science in Sports & Exercise*, *43*, 1042-1049. 10.1249/MSS.0b013e3182035de6

Causer, J., Janelle, C. M., Vickers, J. N., & Williams, A. M. (2012). Perceptual expertise: What can be changed? In N. Hodges & A. M. Williams (Eds.), *Skill acquisition in sport. Research, theory and practice* (pp. 306-324). London: Routledge.

Causer, J., Vickers, J. N., Snelgrove, R., Arsenault, G., & Harvey, A. (2014). Performing under pressure: Quiet eye training improves surgical knot-tying performance. *Surgery*, *156*, 1089-1096. 10.1016/j.surg.2014.05.004

Causer, J., & Williams, A. M. (2013). Improving anticipation and decision making in sport. In P. O'Donoghue, J. Sampaio, & T. McGarry (Eds.), *The Routledge handbook of sports performance analysis* (pp. 21-31). London: Routledge.

Corbetta, M., Patel, G., & Shulman, G. L. (2008). The reorienting system of the human brain: From environment to theory of mind. *Neuron*, *58*, 306-324. 10.1016/j.neuron.2008.04.017

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*(3), 201-215. 10.1038/nrn755

Coren, S., Ward, L., & Enns, J. T. (2003). *Sensation and perception* (6th ed.). New York: John Wiley & Sons.

Dryden, K. (1998). In M. Messier (Ed.), *Wayne Gretzky: The making of the great one*. Dallas, TX: Beckett.

Emes, C., Vickers, J. N., & Livingston, L. (1994). Gaze control of children with high versus low motor proficiency. In K. Yabe, K. Kusano, and H. Nakata (Eds.), *Adapted physical activity: Health and fitness* (pp. 147-154). Tokyo: Springer.

ESPN (2016). *NHL Player Points Statistics 2014-15*. Retrieved 21st January 2016 from http://espn.go.com/nhl/statistics/player/_/st/goaltending/sort/avgGoalsAgainst/year/2015

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion*, *7*, 336-353. 10.1037/1528-3542.7.2.336

Gilovich, T., Tversky, A., & Vallone, R. (1985). The hot hand in basketball: On the misperception of random sequences. *Cognitive Psychology*, *3*, 295-314.

Gonzalez, C. C., Causer, J., Miall, R. C., Grey, M. J., Humphreys, G., & Williams, A. M. (2015a). Identifying the causal mechanisms of the quiet eye. *European Journal of Sport Science*, Epub ahead of print. 10.1080/17461391.2015.1075595

Gonzalez, C. C., Causer, J., Miall, C., Grey, M., Humphreys, G., & Williams, A. M. (2015b). *Identifying the functional mechanisms of the QE in expert and novice archers during aiming tasks*. Paper presented at the 6th International Conference on Spatial Cognition, "Space and Situated Cognition", September 7-11, 2015, Rome, Italy.

Gretzky, W., & Reilly, W. (1990). *Gretzky: An autobiography*. Toronto, Canada: Harper Collins.

Harle, S. K., & Vickers, J. N. (2001). Training quiet eye improves accuracy in the basketball free throw. *The Sport Psychologist*, *15*, 289-305.

Henderson, S. E., Sugden, D. A., & Barnett, A. L. (2007). Movement assessment battery for children. Second Edition (Movement ABC-2). *Examiner's manual* (pp. 125). London: Harcourt Assessment.

Jäncke, L., Koeneke, S., Hoppe, A., Rominger, C., & Hänggi, J. (2009). The architecture of the golfer's brain. *PLoS ONE*, *4*, e4785. 10.1371/

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.

Kahneman, D. (2011). *Thinking fast and slow*. New York: Straus & Giroux.

Klostermann, A., Kredel, R., & Hossner, E-J. (2014). On the interaction of attentional focus and gaze: The quiet eye inhibits focus-related performance decrements. *Journal of Sport & Exercise Psychology*, *36*, 392-400. 10.1123/jsep.2013-0273

Kolb, B., & Whishaw, I. (2009). *Fundamentals of human neuropsychology* (6th ed.). New York: Worth.

Kolb, B., & Whishaw, I. (2013). *An introduction to brain and behavior* (4th ed.). New York: Worth.

Land, M. F. (2009). Vision, eye movements, and natural behavior. *Visual Neuroscience*, *26*, 51-62. 10.1017/S0952523808080899

Liversedge, S. P. (2011). *Oxford handbook of eye movements*. Oxford, UK: Oxford University Press.

Mann, D., Coombes, S. A., Mousseau, M., & Janelle, C. (2011). Quiet eye and the Bereitschaftspotential: Visuomotor mechanisms of expert motor performance. *Cognitive Processing*, *12*, 223-234. 10.1007/s10339-011-0398-8

Mann, D. T., Williams, A. M., Ward, P., & Janelle, C. M. (2007). Perceptual-cognitive expertise in sport: A meta-analysis. *Journal of Sport & Exercise Psychology*, *29*, 457-478.

Miles, C. A. L., Vine, S. J., Wood, G., Vickers, J. N., & Wilson, M. R. (2014). Quiet eye training improves throw and catch performance in children. *Psychology of Sport and Exercise*, *15*, 511-515. 10.1016/j.psychsport.2014.04.009

Miles, C. A. L., Wood, G., Vine, S. J., Vickers, J. N., & Wilson, M. R. (2015a). Quiet eye training aids the long-term learning of throwing and catching in children: Preliminary evidence for a predictive control strategy. *European Journal of Sport Science*, Epub ahead of print. 10.1080/17461391.2015.1122093

Miles, C. A. L., Wood, G., Vine, S. J., Vickers, J. N., & Wilson, M. R. (2015b). Quiet eye training facilitates visuomotor coordination in children with developmental coordination disorder. *Research in Developmental Disabilities*, *40*, 31-41. 10.1016/j.ridd.2015.01.005

Moore, L. J., Vine, S. J., Cooke, A., Ring, C., & Wilson, M. (2012). Quiet eye training expedites motor learning and aids performance under heightened anxiety: The roles of response programming and external attention. *Psychophysiology*, *49*, 1005-1015. 10.1111/j.1469-8986.2012.01379.x

Moore, L. J., Vine, S. J., Wilson, M. R., & Freeman, P. (2012). The effect of challenge and threat states on performance: An examination of potential mechanisms. *Psychophysiology*, *49*, 1417-1425. 10.1111/j.1469-8986.2012.01449.x

Moore, L. J., Wilson, M., Vine, S. J., Coussens, A. H., & Freeman, P. (2013). Champ or chump? Challenges and threat states during pressurized competition. *Journal of Sport & Exercise Psychology*, *35*, 551-562.

LLC (2016). *NBA & ABA career leaders and records for free throw pct.* Retrieved 21st January 2016 from http://www.basketball-reference.com/leaders/ft_pct_career.html

Newell, K. M. (1986). Constraints on the development of coordination. In M. G. Wade & H.T.A Whiting (Eds.), *Motor development in children: Aspects of coordination and control* (pp. 341-361). Amsterdam: Martinus Nijhoff.

Panchuk, D., & Vickers, J. N. (2006). Gaze behaviors of goaltenders under spatial-temporal constraints. *Human Movement Science*, *25*, 733-752.

PGA Tour (2016). *Statistics*. Retrieved 21st January 2016 from http://www.pgatour.com/stats/stat.104.html

Rienhoff, R., Tirp, J., Strauss, B., Baker, J., & Schorer, J. (2015). The "Quiet Eye" and motor performance: A systematic review based on Newell's constraints-led model. *Sports Medicine*, Epub ahead of print. 10.1007/s40279-015-0442-4

Rizzolatti, G., Fadiga, L., Gallese, V., & Fogassi, L. (1996). Premotor cortex and the recognition of motor actions. *Cognitive Brain Research*, *3*, 131-141. 10.1016/0926-6410(95)00038-0

Rodrigues, S. T., Vickers, J. N., & Williams, A. M. (2002). Head, eye and arm coordination in table tennis. *Journal of Sports Sciences*, *20*, 187-200.

Sibor, D. (2013). *The 25 best short athletes of all time*. Retrieved 21st January 2016 from http://ca.complex.com/sports/2013/03/the-best-little-men-in-sports-history/

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*, 97-136. 10.1016/0010-0285(80)90005-5

Vickers, J. N. (1988). Knowledge structures of elite-novice gymnasts. *Human Movement Science*, *7*, 47-72.

Vickers, J. N. (1992). Gaze control in putting. *Perception*, *21*, 117-132.

Vickers, J. N. (1996a). Control of visual attention during the basketball free throw. *American Journal of Sports Medicine*, *24*(6 Suppl.), s93-s97.

Vickers, J. N. (1996b). Location of fixation, landing position of the ball and spatial visual attention during free throw shooting. *International Journal of Sports Vision*, *3*, 54-60.

Vickers, J. N. (1996c). Visual control when aiming at a far target. *Journal of Experimental Psychology. Human Perception and Performance*, *22*, 342-354.

Vickers, J. N. (2007). *Perception, cognition & decision training: The Quiet Eye in action*. Champaign, IL: Human Kinetics.

Vickers, J. N., & Adolphe, R. (1997). Gaze behaviour during a ball tracking and aiming skill. *International Journal of Sports Vision*, *4*, 18-27.

Vickers, J. N., & Williams, A. M. (2007). Performing under pressure: The effects of physiological arousal, cognitive anxiety, and gaze control in biathlon. *Journal of Motor Behavior*, *39*, 381-394.

Vine, S. J., Lee, D., Moore, L. J., & Wilson, M. R. (2013). Quiet eye and choking: Online control breaks down at the point of performance failure. *Medicine & Science in Sports & Exercise*, *45*, 1988-1994. 10.1249/MSS.0b013e31829406c7

Vine, S. J., & Wilson, M. (2011). The influence of quiet eye training and pressure on attention and visuo-motor control. *Acta Psychologica*, *136*, 340-346. 10.1016/j.actpsy.2010.12.008

Wilson, M., Causer, J., & Vickers, J. N. (2015). Aiming for excellence: The quiet eye as a characteristic of expertise. In J. Baker & D. Farrow (Eds.), *Routledge handbook of expertise* (pp. 22-37). New York: Routledge.

Wilson, M. R., Miles, C. A., Vine, S. J., & Vickers, J. N. (2013). Quiet eye distinguishes children of high and low motor coordination abilities. *Medicine & Science in Sports & Exercise*, *45*, 1144-1151. 10.1249/MSS.0b013e31828288f1

Wood, G., & Wilson, M. (2011). Quiet-eye training for soccer penalty kicks. *Cognitive Processing*, *12*, 257-266. 10.1007/s10339-011-0393-0

Woolley, D. G., Wenderoth, N., Heuninckx, S., Zhang, X., Callaert, D., & Swinnen, S. P. (2010). Visual guidance modulates hemispheric asymmetries during an interlimb coordination task. *Neuroimage*, *50*, 1566-1577. 10.1016/j.neuroimage.2010.01.012

World Archery (2016). *Statistics*. Retrieved 21st January 2016 from http://worldarchery.org

Wright, M. J., Bishop, D. T., Jackson, R. C., & Abernethy, B. (2010). Functional MRI reveals expert-novice differences during sport-related anticipation. *Neuroreport*, *21*(2), 94-98. 10.1097/WNR.0b013e328333dff2

Wright, M. J., Bishop, D. T., Jackson, R. C., & Abernethy, B. (2011). Cortical fMRI activation to opponents' body kinematics in sport-related anticipation: Expert-novice differences with normal and point-light video. *Neuroscience Letters*, *500*(3), 216-221. 10.1016/j.neulet.2011.06.045

Wright, M. J., & Jackson, R. C. (2007). Brain regions concerned with perceptual skills in tennis: An fMRI study. *International Journal of Psychophysiology*, *63*, 214-220. 10.1016/j.ijpsycho.2006.03.018